

Research Paper

Predicting design water requirement of winter paddy under climate change condition using frequency analysis in Bangladesh

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ABSTRACT

The effects of climate change on the agricultural sector are tremendous. Thus, it is essential to determine its impacts on agricultural water resources and to minimize adverse effects on crop production. The present study aims to simulate climate data based on SRES A1B scenario from the outputs of three General Circulation Models (GCMs) namely, FGOAL, HADCM3 and IPCM4 and examine the design water requirement (DWR) of winter paddy using frequency analysis under climate change condition in Bangladesh. The average change rates of DWR in four climatic zones were compared to baseline and the results were −12.16% (2020s), −0.28% (2055s), and 1.25% (2090s) for the FGOAL, −4.44% (2020s), 0.57% (2055s) and 1.25% (2090s) for the HADCM3, and −1.12% (2020s), 2.22% (2055s) and 6.69% (2090s) for the IPCM4. The change rates of gross paddy water demand (GPWD) for three GCMs ranged from −3.01% to 11.16%. In both cases of the DWR and GPWD, the change rates were above 3%, indicating a warning signal to the future winter paddy water management. The outcomes of this study can be used as basic data for the development of agricultural water resource management, which will help to minimize the drought-risk and to implement future agricultural water resource policies in Bangladesh.

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1. Introduction

Nowadays, climate change is one of the greatest threats that our planet faces. Climate change directly affects global and regional agriculture and irrigation systems (Puma and Cook, 2010; Hong et al., 2016). It is generally accepted that the agricultural sector of developing countries are more vulnerable to climate change than developed countries, mostly because of low capacity and infrastructure to adapt to changing climate. Being a developing country, Bangladesh is also facing tremendous challenges from climate change, particularly for its agricultural based economy. Consequently, irrigation water requirements in Bangladesh will increase in the upcoming decades due to the rises in temperature, changes in rainfall pattern and solar radiation. In addition, agricultural sector of Bangladesh is expected to face rising competition for water resources from other sectors. According to the Ministry of Water Resources of Bangladesh, 86% of total water usage is attributed to

the agricultural sector, and 70% is consumed to paddy rice cultivation (Chowdhury, 2010). The design water requirement of paddy rice is vital to the optimal design and operation of agricultural water resources systems. However, profound knowledge regarding the change rates of design rice water requirement at regional and national levels in Bangladesh is still significant for the better understanding of climate change and its multidimensional impacts.

Bangladesh has now become a self-sufficient rice producing country because irrigation has intensified rice production. Winter rice is one of the main dry season crops of Bangladesh, which fully depends on irrigation. The total amount of water used for winter rice has increased considerably over the last three decades because of intensive irrigated agriculture in Bangladesh. Intensive irrigated agriculture is the outcome of water shortages during dry seasons from January to April (Shahid, 2008). Additionally, groundwater is heavily used for irrigated agriculture due to shortage of surface water resources, and this has led to decline of groundwater levels during the dry season. Any change of rice water requirement as affected by climate change, and then, needs to be thorough studied and the results require managing rice water requirement. Drought risk (Shahid and Behrawan, 2008), groundwater sustainability (Kirby et al., 2015), and future climate change impacts (Mainuddin et al., 2015; Kirby et al., 2016) are considered serious challenges for irrigation water management, and they

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have recently received the significant attention in Bangladesh. Hence, irrigation water management in Bangladesh has concentrated mainly on protecting the paddy rice areas from the possible risk of drought under climate change, because sustaining food security and further increasing paddy rice production in Bangladesh is considered a top priority.

The present study has focused solely on one of the most critical factors, namely the effects of future climate change on design water requirement of paddy rice. In order to be able to adapt to the changing climate, a clear understanding of water requirement changes in response to the variations in the climate variables can help in the planning and management of agricultural water resources (IPCC, 2014; Wang et al., 2015). As the agricultural sector is a climate-sensitive, it is necessary to understand how climate change affects agricultural water resources for sustainable agriculture, particularly paddy rice production in Bangladesh. Future water security depends on climate change and water requirements for irrigation (Hong et al., 2016). It is essential to know how much water is required for irrigation to help agricultural sustainability and food security under current and future climate change scenarios.

Bangladesh is already recognized as one of the worst victims of climate change (IPCC, 2007). The IPCC (2007) predicts that climate patterns in Bangladesh will change due to the rising global temperature. The rainfall, temperature and solar radiation vary with season to season and location wise. Each year Bangladesh face mild to severe drought, for instance, northwestern area has been known as drought prone regions of the country (Islam et al., 2017). Drought is very sensitive to climate and varies in year to year. One of the important problem in drought analysis deals with past record of an events in terms of future probabilities of occurrence. The procedure for estimating frequency of occurrence of a drought event is usually done by frequency analysis. Though rainfall is erratic in nature, temperature varies season with time and space, it is possible to predict design water requirement (DWR) under climate change condition using frequency analysis. In fact, drought frequency analysis is a basic tool for safe and economic planning and design of future agricultural water management. Hosking and Wallis (1997) reported that planning for water related management, design of irrigation structure; all rely on knowledge of the frequency of the extreme events such as drought, storm and flood. There is no widely accepted procedure to predict the DWR under climate change condition. This is why the evaluation of design water requirement as embodied with probability distribution function (PDF) relationship has been a major focus of both theoretical and applied agricultural water resources management. Anticipating the effects of climate change and adapting to them is one of the ways to reduce vulnerability to the potential adverse impacts (Prodanovic and Simonovic, 2007). So, a frequency analysis has an application for predicting the design water requirement on probability basis that is irreplaceable.

It is generally acknowledged that General Circulation Models (GCMs) are the key tools to assess future climate change at large scale (Xu, 1999). The main limitation of GCMs is the coarse horizontal resolution, which limits their capability to resolve processes at local scale (Wilby and Wigley, 1997). To resolve this problem, it is of necessary to adjust the changes of large-scale predictions of GCMs to the changes of local-scale climate variables. The technique used to convert GCM outputs into local climate variables are generally done by downscaling methods. There are various methods for downscaling GCMs outputs which fall into two categories e.g. (i) dynamic and (ii) statistical downscaling (Fowler et al., 2007). Among several downscaling methods, LARS-WG (Long Ashton Research Station Weather Generator) (Semenov et al., 1998) model has the advantage of less data require and has been extensively used in the climate change impact studies (Islam et al., 2017; Kumar et al., 2014). Another advantage is that 15 GCMs outputs

with various scenarios have been included in the LARS-WG model to better dealing with GCMs uncertainties.

Several studies have been carried out on future water requirements of paddy rice affected by climate change at local and global scales, which can be found in literature. For example, De Silva et al. (2007) assessed the paddy irrigation water requirement (IWR) in Sri Lanka and the IWR predicted by 13–23% increase under SRESB2 and A2 scenarios using datasets from the HADCM3 outputs. Rodriguez Diaz et al. (2007) studied in the Guadalquivir Basin in Spain and found that the seasonal IWR would be increased between 15% and 20% by the 2050s under A2 and B2 scenarios. Elgaali et al. (2007) modeled in the Arkansas Basin in Colorado and projected irrigation water demand an increase of 5% (2050s) and 9% (2090s) when using the HadCM2 GCMs outputs. Chung et al. (2011) projected the total volumetric decreases of 4% (2050s) and 10% (2080s) of the IWR in South Korea based on the HadCM3 outputs for the A2 and B2 scenarios. Yoo et al. (2012) also projected the average change rates of the design water requirement (DWR) of wet season paddy below 3% under SRES A1B, A2 and B1 scenarios in South Korea when using climate datasets from the CGCM 3.1 GCMs outputs. Gondim et al. (2012) in the Jaguaribe River Basin, Brazil and Rehana and Mujumdar (2013) in Bhadra reservoir area in India found the impacts of climate change to be increased of paddy rice IWR and a change in crop evapotranspiration (ETc). Lee and Huang (2014) predicted an increase of 7% (2050s) of IWR of paddy rice in Taiwan. Hadinia et al. (2016) studied climate change impacts on rice water requirement in Iran and found that average rice water requirement will increase for the upcoming periods. Most of the previous studies predicted that rice water requirement will increase under climate change scenarios, even though the effect of projected changes in rainfall on the IWR is offsetting by the effect of projected changes in other climate variables such as temperature, solar radiation.

In Bangladesh, Shahid (2011) predicted the changes of the IWR in the dry season *Boro* rice field in northwest Bangladesh under SRES B2 scenario. Mainuddin et al. (2015) estimated the impact of climate change on the IWR of dry season crops in Bangladesh and confirmed to increase by a maximum of 3% of the *Boro* paddy IWR for the 2050s dry condition using the A1B scenario based on the HADCM3 and FGOALS GCM outputs. Recently, Acharjee et al. (2017) investigated the future impacts of climate change on the IWR of dry season *Boro* rice in north-west Bangladesh and found that net irrigation requirement of *Boro* rice will decrease by 1.6% in 2050s and 7.4% in 2080s using the RCP 8.5 scenario based on five GCM models. These earlier studies in Bangladesh have focused on the changes of crop evapotranspiration (ETc) and the net irrigation requirement (NIR). However, the study of design water requirement for paddy rice under climate change condition has not been undertaken in Bangladesh. Therefore, the research of climate change impacts on the DWR for winter paddy rice in Bangladesh, which accounts for a maximum agricultural water usage, need to be introduced as a matter of concern.

Motivated by the above-mentioned facts, the main objective of this study is to predict design water requirement and gross water demand for winter paddy rice in the major climatic zones of Bangladesh under climate change. We simulated a database of future climate data (2011–2099) using the three GCMs outputs and downscaled by the LARS-WG model under SRES A1B scenario. This study focuses on changes in the spatial and temporal trends in the DWR of winter paddy in Bangladesh. However, for the first time in Bangladesh, a study of climate change-predicting design water requirement using frequency analysis for winter paddy rice has been carried out. It is anticipated that this study will be guideline for regional water managers, agriculturalists and decision makers in understanding the impacts of future climate change and also

contributes to implement agricultural water resource policies in Bangladesh for achieving sustainable food security.

2. Data and methods

In this study, the daily historical climate data (e.g., minimum and maximum temperature, rainfall and sunshine hours as well as solar radiation) were collected from the Bangladesh Meteorological Department (BMD) for a 30-year period (1984–2013). The procedures for calculating design water requirement (DWR) are displayed in Fig. 1.

2.1. Study area and climatic zones of paddy rice

The study area is located between India and Myanmar in South-east Asia ($20^{\circ}34'–26^{\circ}38'$ N latitude and $88^{\circ}01'–92^{\circ}41'$ E longitude). Bangladesh enjoys the subtropical monsoon climate, and has four distinct seasons including winter, spring, summer and autumn (Islam et al., 2017). About 80% of the country's annual rainfall occurs during the summer season, and the annual average total rainfall is 2428 mm. The annual average temperature is 25.7°C , where the lowest temperature is 7.2°C in January and the highest temperature is 31.1°C in August obtained from the Bangladesh Meteorological Department (BMD).

Three rice cropping patterns such as winter rice (Boro), summer rice (Aus) and monsoon rice (Aman) are distributed widely in Bangladesh according to climatic responses. We considered only winter paddy rice (rice grown from December to May) because this rice variety covers about 86% of irrigated area and also supplying about 95% of the total water for irrigation. However, summer rice and monsoon rice may occasionally need supplementary irrigation (only occupying about 3% of irrigated area). For this reason, we ignore those rice cropping patterns in the present study. The total cultivated winter paddy rice area has increased from 1.6 million ha (1984) to 5.5 million ha (2013); winter rice produced about 58% of total production in 2013; and the paddy area has changed significantly during the last 30-years period (BBS, 2014). Bangladesh Meteorological Department (BMD) has 34 weather stations, although all stations do not have long-term observed data record because some of them are newly established and few stations have missing data for long periods. In this study, 10 meteorological stations were selected which represent major climatic zones of winter paddy rice areas (Fig. 2 and Table 1). Bangladesh has divided into seven climatic zones that are suggested by National Encyclopedia of Bangladesh (Banglapedia, 2003). Out of seven zones, four climatic zones (zone-C, D, F and G) were taken into consideration using 10 meteorological station climate data, which account for the 73.6% share of winter rice area (Table 2). The highest paddy area ratio was found in south-central region (zone-F) and the lowest was observed in western region (zone-E) of Bangladesh (Table 2). This study mainly focused on the zone-C, D, F and G, which have relatively larger share of paddies. In the present study, four climatic zones were used to estimate the DWR for better illustration of spatial variations.

2.2. Climate datasets generation

Temperature is expected to increase in the Ganges basin (Moors et al., 2011), whereas the trend for rainfall is less certain in Bangladesh; although, rainfall is projected to increase in some cases (Yu et al., 2010). There is uncertainty in the magnitude of the increased climate variables that vary with GCMs and with emission scenarios and also decreases are possible. In Bangladesh, extreme temperature and rainfall are projected to increase in future period (Kumar et al., 2006). In view of the uncertainty, we chose to use three GCMs (HADCM3, FGOALS-g1.0 and IPCM4) for this study.

The main advantage of using three GCMs is that these can be used to compare weather data for projecting crop simulation (Reddy and Pachepsky, 2000). These three GCMs provide a valuable dataset for climate change impact application, particularly agriculture water resource management. They are considered to be the most mature and popular GCMs among others (Toews and Allen, 2009) because they have been frequently used in agricultural crop risk assessment in many parts of the world including Bangladesh (Bannayan and Eyshi Rezaei, 2014; Islam et al., 2017). Although GCMs contain significant uncertainties but they are very useful for predicting future climate under different conditions (Wilby et al., 1999). Furthermore, these GCMs have been extensively used in statistical downscaling of climate variables over Bangladesh (Shahid, 2011; Kumar et al., 2014; Mainuddin et al., 2015).

The new version of LARS-WG (5.5) is capable of incorporating into 15 GCMs with different scenarios used in the IPCC AR4. Among the 15 GCMs, three GCMs were employed in the study based on SRES A1B scenario that it sees the future world as balances one which is characterized by rapid economic growth and introducing new efficient technology. The IPCC Data Distribution Center provides the three GCMs outputs based on the SRES A1B scenario (<http://www.ipcc-data.org>). The GCMs that provide an outcome of the A1B scenario applied for the IPCC AR4 were chosen: FGOALS-G1.0 (China), HADCM3 (UK) and IPCM4 (France). The outputs from three GCMs climate models are utilized in this study, which are summarized in Table 3. For this purpose, daily rainfall, minimum and maximum temperature and sunshine hour data for the study area for the time period (1984–2013) were utilized. The predicted changes in climate and their impacts need to be assessed relative to the baseline. The baseline climate (1984–2013) is significantly different from the climate in the past years, for example, 1961–1990. It is noted that the new version of LARS-WG (5.5) model is allowed to use different baseline period. So, the daily observed weather data have been and continue to be used as reference (baseline period) climate in some studies of climate change (Kumar et al., 2014; Hadinia et al., 2016).

2.3. LARS-WG model

LARS-WG is a stochastic weather generator and is used as a statistical downscaling method for simulating weather data at a single site under both current and future conditions (Semenov et al., 1998). The LARS-WG uses the observed daily weather data for a given site to compute a set of parameters for fitting probability distributions as well as correlations between them which are employed to generate synthetic weather time series of arbitrary length by randomly selecting values from the appropriate distributions. The LARS-WG model was downloaded from Department of Computational and Systems Biology, Rothamsted Research, UK website (www.rothamsted.ac.uk).

The process of generating synthetic weather data using LARS-WG model is divided into three steps:

First, the calibration of LARS-WG model is done by using "SITE ANALYSIS" function, which analyzes observed historical data for the period of 1984–2013 (e.g. rainfall, temperature and radiation) at each station to determine their statistical characteristics and stores this information in two parameter files.

Second, the parameter files derived from observed weather data during the model calibration process are used to generate synthetic weather data having the same statistical characteristics as the historical observed data. The validation of LARS-WG model is to analyze and compare the statistical characteristics of the observed and synthetic weather data to assess the ability of model to simulate rainfall, maximum and minimum temperature and solar radiation at selected sites to determine whether or not it is suitable for use in the present study.

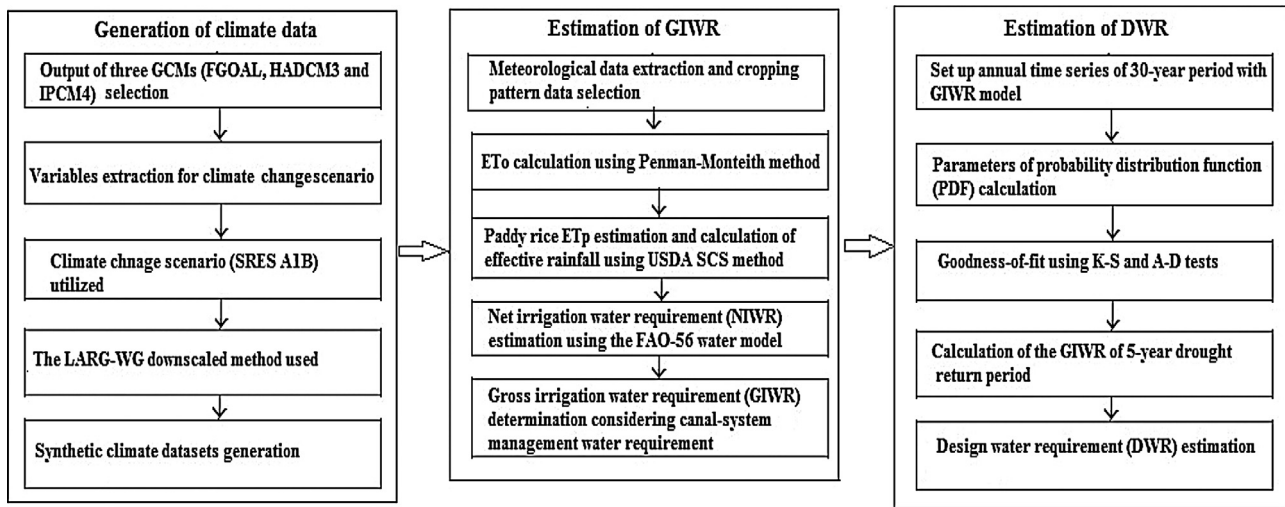


Fig. 1. A systematic flow chart diagram for estimating DWR under climate change condition.

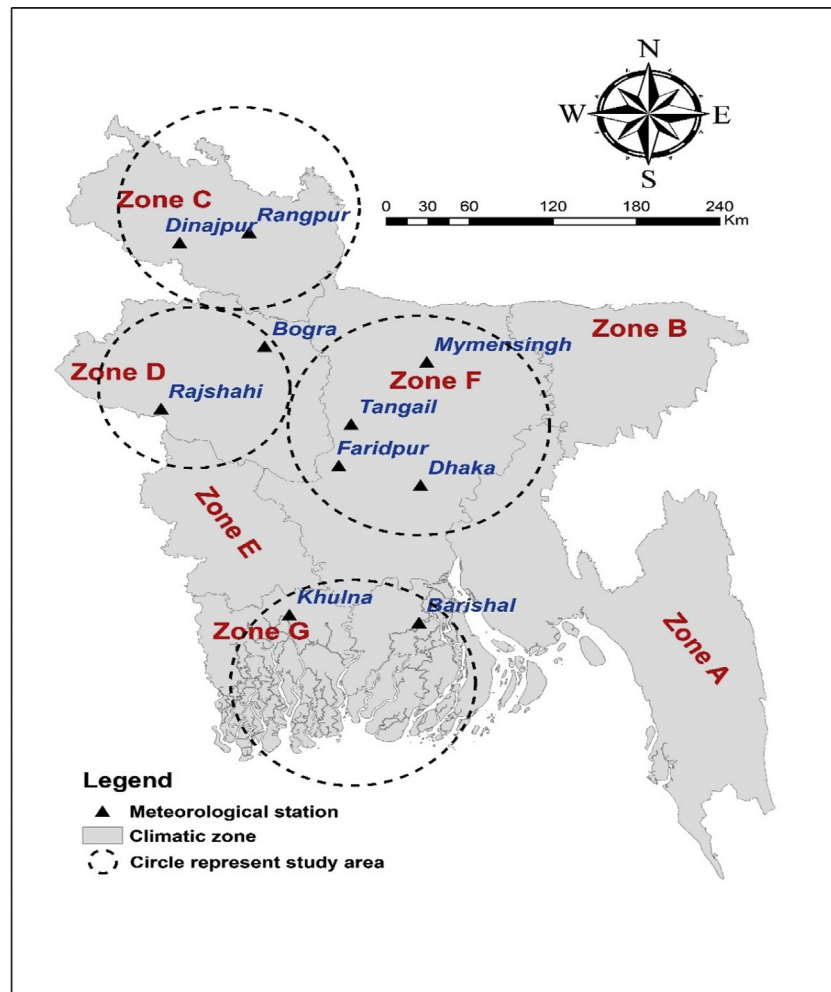


Fig. 2. Location map showing meteorological station, climatic zones of paddy rice in Bangladesh.

Third, the parameter files derived from observed weather data during the model calibration process are also used to generate synthetic data but differing on a day to day basis which is similar to a particular climate change scenario simulated by GCMs.

To generate climate scenario at a given site for a certain future period and an emission scenario, the LARS-WG baseline parameters, which are calculated from observed weather for the site for a

baseline period, for instance, 1984–2013, are adjusted by the Δ -changes for the future period and the emissions predicted by a GCM for each climatic variable for the grid covering the site. In the study, the local-scale climate scenario based on the SRES A1B scenario simulated by the selected three GCMs are downscaled by the LARS-WG (5.5) for three time periods (2011–2030, 2046–2065 and 2080–2099) to predict the future change of rainfall, temperature

Table 1
The information of meteorological station and climate characteristic of winter paddy rice-growing season over the 30-year period (1984–2013) in study sites.

Region	Station	Longitude	Latitude	Alt (m)	Mean min temp (°C)	Mean max temp (°C)	Total seasonal rainfall (mm)
Northern	Rangpur	89.25	25.73	32.6	16.01	28.01	211.10
	Dinajpur	88.68	25.65	37	15.91	28.56	131.43
Northwestern	Bogra	89.36	24.85	20	17.09	29.43	142.60
	Rajshahi	88.70	24.37	19.5	16.48	30.55	109.26
Southcentral	Tangail	89.93	24.25	10.2	20.25	30.60	210.56
	Faridpur	89.85	23.60	9	17.81	30.10	209.66
	Dhaka	90.38	23.76	9	18.87	30.14	245.13
	Mymensingh	90.43	24.71	19	17.20	28.58	236.03
Southwestern	Khulna	89.53	22.78	4	20.75	30.48	240.10
	Barishal	90.36	22.75	4	18.16	30.22	202.20

Table 2
Climatic zones of Bangladesh and paddy area ratios (Banglapedia, 2003) Paddy area data for 2013.

Climatic zones	Name of zones	Winter rice area (million hector)	Ratio (%)
A	Southeastern	0.58	12.1
B	Northeastern	0.41	8.5
C	Northern	0.76	15.8
D	Northwestern	0.59	12.3
E	Western	0.28	5.8
F	Southcentral	1.45	30.3
G	Southwestern	0.73	15.2
	Total	5.51	100.0

Source: Agriculture wings, Bangladesh Bureau of Statistics, (BBS, 2014)

Table 3
Summary of observed and simulated climate data and three General Circulation Models (GCMs) outputs incorporated into the LARS-WG 5.5 version in this study.

Category	Period	Source	Climate model	Grid resolution (lat × long)
Observed data	1984–2013	BMD (Bangladesh Meteorological Department)	Historical data	–
Simulated data	2011–2099	IPCC AR4 Data Distribution Centre (A1B scenario)	FGOALS-g1.0 (China)	2.8° × 2.8°
			HADCM3 (UK)	2.5° × 3.75°
			IPCM4 (France)	2.5° × 3.75°

and solar radiation and to examine the DWR of winter paddy rice. More detailed description of the LARS-WG modeling procedure can be referred to [Semenov \(2002\)](#).

2.4. Gross irrigation water requirement

GIWR is the sum of net irrigation water requirement (NIWR) and canal-system management water requirement (CMW) for paddy rice fields as given in Eq1.

$$GIWR = NIWR + CMW = \frac{NIWR}{1 - WLRC} \tag{1}$$

where, NIWR is net irrigation water requirement (mm) and WLRC is water loss ratio (%) in canal-system water management.

CMW includes conveyance losses, delivery losses and maintenance water losses. [Khan \(1992\)](#) reported it in irrigation management system in Bangladesh, as from 20% to 25% of the net irrigation water requirement for earth lining canal network. [Jang et al. \(2007\)](#) applied a constant water loss ratio 20% to predict gross water demand for the paddy rice fields in South Korea. In this study, we assumed a water loss ratio of 20% for estimating the GIWR of each zone in Bangladesh. Then, we calculated the volumetric gross paddy water demand (GPWD) for each climatic zone by multiplying the estimated the GIWR (mm) by the paddy area (ha). For scenario analysis, the areas are taken as the 2012–2013 winter paddy rice areas based on climatic zones ([BBS, 2014](#)).

2.4.1. Net irrigation water requirement

We calculated the NIWR of the paddy rice field of each zone using the FAO-56 water balance model. [Shahid \(2011\)](#) was applied this model for calculating NIWR in the paddy *Boro* rice field in north-

west Bangladesh. The water balance model of the paddy rice field can be expressed in the following Eq2.

$$NIWR = ET_p + L_p + W_d + P_s - ERF \tag{2}$$

where, ET_p is crop evapotranspiration (mm), L_p is water requirement for land preparation (mm), W_d is water depth to establish ponding water level (mm), P_s is the percolation and seepage losses of water in paddy field (mm), and ERF is the effective rainfall (mm).

2.4.1.1. Crop evapotranspiration. We estimated the reference evapotranspiration (ET_o) on a daily basis using the climate data and the Penman–Monteith equation, as recommended by the FAO ([Allen et al., 1998](#)) and as shown in Eq3. ET_p is estimated by multiplying ET_o and the crop coefficient (K_c) for the same day, as shown in Eq4.

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\left(\frac{900}{T} + 273\right)u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{3}$$

$$ET_p = K_c \times ET_o \tag{4}$$

where, ET_o is reference crop evapotranspiration (mm/day), Δ the slope of saturated vapor pressure curve ($KPa/^\circ C$), γ the psychrometric constant ($KPa/^\circ C$), u_2 the wind speed at 2 m height (m/s), R_n the net radiation at the crop surface (MJ/m^2), G the soil heat flux density(MJ/m^2 day), T the mean daily air temperature at 2 m height ($^\circ C$), e_s the saturation vapor pressure(KPa), and e_a the actual vapor pressure(KPa). In general, the daily G (soil heat flux density) value is nearly zero for estimating daily ET_o . It is very small compared to R_n (net radiation) which ignores in this study for daily ET_o calculation ([Allen et al., 1998](#)).

In this study, we computed two missing parameters such as relative humidity and wind speed following the recommendations of

Allen et al. (1998). The crop coefficient values were taken from the FAO Irrigation and Drainage Paper No.56 due to unavailability of local crop coefficient values in Bangladesh. The transplanting days and total irrigation periods of winter rice are defined as the end of December, and starting from January 01 to May 5.

2.4.1.2. Land preparation and standing water level. Land preparation requires for cultivation of the paddy rice fields in Bangladesh. Generally, land is prepared in the end of December for irrigating dry season winter rice at the beginning of January. A land preparation water depth of 150 mm to 200 mm was recommended to use for paddy rice transplanting in Bangladesh (Meharg and Rahman, 2003). Thus, we assumed a land preparation water level of 150 mm for this study according to the national irrigation water design standards (BADC, 2010). The standing water depth of 50 mm to 70 mm in the rice field is expected for better winter rice yield during irrigation period (Banglapedia, 2003). We considered a water depth of 50 mm to establish standing water depth for winter rice fields in Bangladesh.

2.4.1.3. Percolation and seepage losses. The most of the paddy rice irrigation systems are developed in clay soil that have low percolation rates in Bangladesh. Various experiments results demonstrated that average percolation rate varied from 3 to 6 mm/day between 30 and 70 mm standing water depth during crop growing period (BRRI, 1990). Mainuddin et al. (2015) applied 3.0 mm/day of water percolates into paddy clay loam soil for the Boro rice field in Bangladesh during irrigation season. We assumed a 3.0 mm/day percolation rate of paddy rice field.

2.4.1.4. Effective rainfall. Several universal empirical methods have found in the literature for estimating effective rainfall (Kuo et al., 2006), e.g. fixed percentage of rainfall, dependable rainfall, empirical formula, and USDA Soil Conservation Service Method (USDA-SCS). In this study, we estimated effective rainfall using the empirical USDA-SCS method. This method was applied for modeling paddy irrigation requirement in India (Mohan et al., 1996), Taiwan (Kuo et al., 2006) and South Korea (Chung et al., 2011) as given below in Eq. (5–6)

$$R_{\text{eff}} = R_{\text{tot}} \times \frac{125 - 0.2R_{\text{tot}}}{125}, \text{ for } R_{\text{tot}} < 250\text{mm} \quad (5)$$

$$R_{\text{eff}} = 125 + 0.1 \times R_{\text{tot}}, \text{ for } R_{\text{tot}} > 250\text{mm} \quad (6)$$

where, R_{eff} is the effective rainfall (mm), R_{tot} the total rainfall of the paddy rice-growing season (mm).

2.5. Design water requirement

2.5.1. Drought of a 5-year return period and drought reference year

In the last 50 years, irrigation systems in Bangladesh are vulnerable to drought risk for sequential years. These sequential droughts have occurred once in a period of 5 years: 1965–1966, 1972–1973, 1978–1979, 1983–1984, 1989–1990, 1994–1995, 1999–2000 and 2006–2007. Parvin and Saleh (2013) showed that average frequency of drought is about once in a 5-year return period using probability analysis of rainfall and crop water requirements in northwestern Bangladesh. Therefore, we considered a 5-year return period of a drought as a benchmark for estimating DWR for the design of agricultural water resource systems in Bangladesh.

2.5.2. Frequency analysis

We performed frequency analysis considering a 5-year return period drought in the study. Yoo et al. (2012) applied the Generalized Logistic (GLO) probability distribution function (PDF) for

frequency analysis in South Korea and also similar procedure was adopted for this study. The procedures involved for frequency analysis are as follows: first, we constructed a time series of yearly GIWR for each zone for the three GCMs with A1B scenario ranging from 1984 to 2013 and the time periods of 2011–2099. Then, the Weibull (WBU) PDF parameters were calculated using by maximum likelihood method (MLM) as recommended by FEMA (2005). Third, we examined the goodness-of-fit using the Kolmogorov-Smirnov (K-S) and Anderson-Darling (A-D) tests with data of each zone. Finally, we estimated the DWR of a 5-year return period drought using the chosen optimal distribution function (PDFs) and Chow frequency factor method (Chow, 1951). The frequency factor method is expressed in the following Eq. (7)

$$X_T = x + \sigma K_T \quad (7)$$

where, X_T is a variate, x a mean, σ a standard deviation, K a frequency factor while T is a return period. The frequency factor can be determined from K-T relationship for a specific distribution and magnitude, X for the return period can be formulated using Eq. (7) for a given return period, using frequency factor, and the computed statistical parameters. The procedures involved in determining parameters of PDFs and a return period estimation using the maximum likelihood method (MLM) are briefly described by Rao and Hamed (2000).

2.6. Calibration and validation of LARS-WG model

The daily observed data during the period of 1984–2013 were used to calibrate and validate the LARS-WG model for 10 selected stations of Bangladesh, which represent the four climatic zones. To evaluate the ability of LARS-WG, in addition to the graphical comparison, several statistical tests are also carried out. The Kolmogorov-Smirnov (K-S) goodness-of-fit test is done on testing equality of the seasonal distributions of wet and dry series (WDSeries), distributions of daily rainfall (RainD), and distributions of daily maximum (TmaxD), minimum (TminD), and daily radiation (RadD) calculated from observed weather data and generated downscaled data. The t test is done on testing equality of monthly mean rainfall (RMM), monthly mean of daily maximum temperature (TmaxM), monthly mean of daily minimum temperature (TminM) and monthly mean of daily radiation (RadM). The F -test is done on testing equality of monthly variances of rainfall (RMV) calculated from observed weather data and generated data. A p -value of 0.05 is the significance level used in this study.

The test results present in Table 4, where the numbers show how many tests give significantly different results out of the total number of tests of 8 or 12 at the 5% significance level. A small number indicates a good performance of the LARS-WG model. It is seen from Table 4 that the average number of significant different results for WDSeries was 0.7 out of eight; the average number of significant results for the RainD is 1.8 out of 12; for the RMM is 1.5 out of 12; and for the RMV is 1.6 out of 12, respectively. The average numbers of significant results for TminD, TminM, TmaxD, TmaxM, RadD and RadM are either zero or close to 0.2. From these numbers, it can be said that the LARS-WG model is more capable of simulating the monthly means and the daily rainfall, temperature and solar radiation distributions of each month compared to the monthly variances.

The comparison of monthly mean of the generated and observed rainfall is shown in Fig. 3 for 10 representative stations as an example. Fig. 3 depicts that there are good matches between the monthly mean of the generated and observed rainfall. Therefore, the new version of LARS-WG (5.5) has great capacity in simulating rainfall and also temperature.

Table 4

Results of the statistical tests comparing the observed historical data for 10 stations with synthetic data generated through the LARS-WG model for the seasonal distributions of wet and dry series (WDSeries), distributions of daily rainfall (RainD), monthly mean rainfall (RMM) and its variances (RMV), and distributions of daily maximum (TmaxD) and minimum (TminD) temperature and their monthly means (TmaxM and TminM), distributions of daily solar radiation (RadD) and its monthly mean (RadM). Distributions were compared using the K-S test, and means and variances were compared using the t-test and F-test, respectively. The numbers in this table display how many tests provided significant results at 5% level of significance. A small number of significant results show a good performance of the weather generator.

Zone	Station	WDSeries	RainD	RMM	RMV	TminD	TmaxM	TmaxD	TmaxM	RadD	RadM
C	Rangpur	0	3	4	4	0	1	0	0	0	0
	Dinajpur	2	2	0	0	0	0	0	0	0	1
D	Bogra	1	4	1	1	0	0	0	0	0	1
	Rajshahi	0	1	1	1	0	0	0	0	0	0
F	Tangail	0	2	0	1	0	0	0	0	0	0
	Faridpur	0	1	2	2	0	0	0	0	0	0
	Dhaka	1	3	3	3	0	0	0	0	0	0
	Mymensingh	1	0	1	1	0	0	0	0	0	0
G	Khulna	1	1	3	3	0	0	0	0	0	0
	Barishal	1	1	0	1	0	0	0	1	0	0
	Average	0.7	1.8	1.5	1.6	0	0.1	0	0.1	0	0.2
Total tests		8	12	12	12	12	12	12	12	12	12

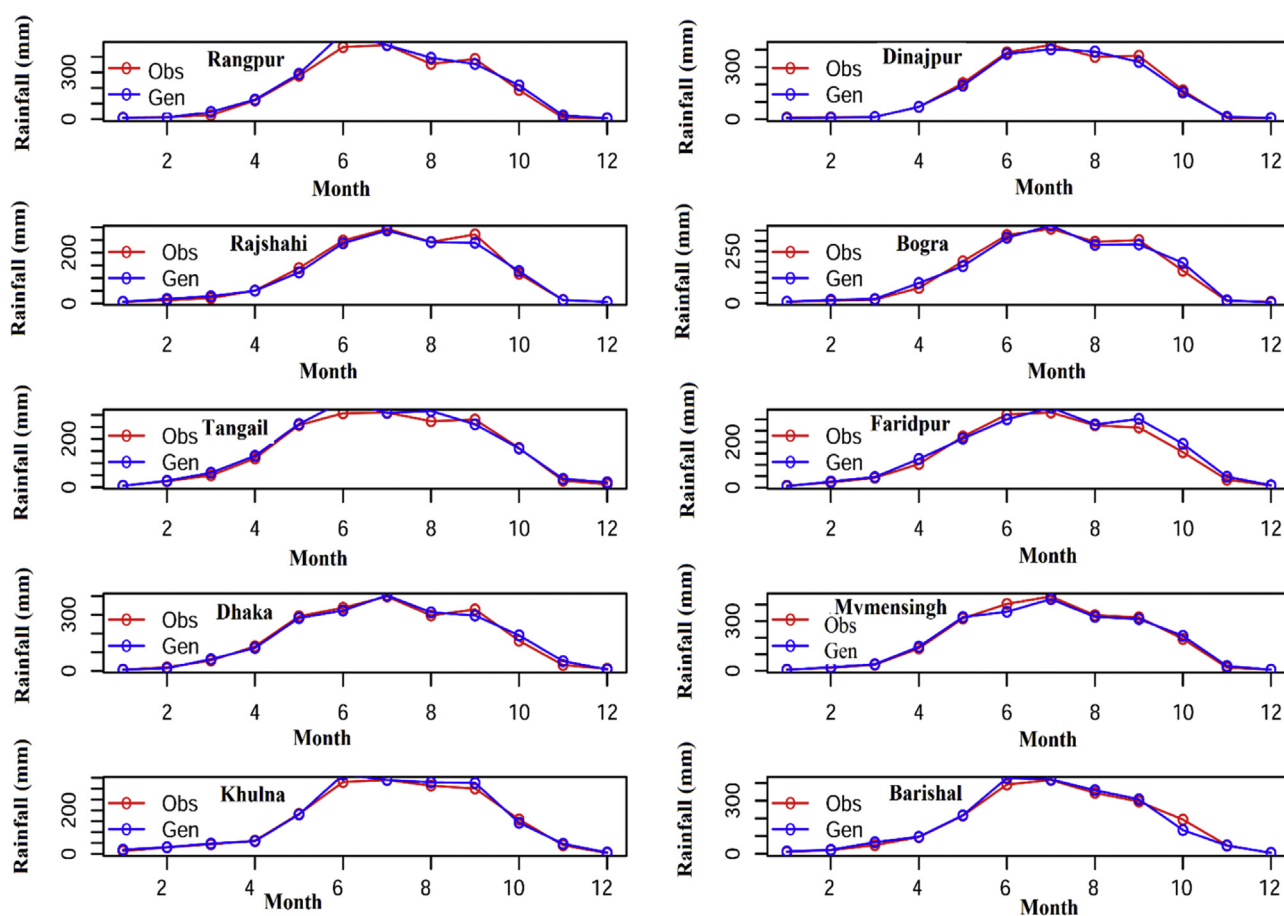


Fig. 3. Comparison of the mean monthly observed and the LARS-WG generated rainfall (mm) at each station in the period 1984–2013.

3. Results and discussions

3.1. Projected monthly weather variations under climate change

Mean temperature was calculated from the projected maximum and minimum temperatures. The IPCM4 GCMs of the 2090s showed the highest temperature increase of 27.19°C, while the FGOAL GCMs of the 2090s exhibited the lowest temperature increase of 25.66°C in comparison to baseline. Temperature increased by 2.35–3.65°C, 1.86–3.30°C, 1.66–3.2°C, 1.72–3.57°C, 1.82–3.42°C,

and 1.85–3.29°C in the month of December, January, February, March, April and May respectively during paddy rice-growing seasons of the 2090s periods (See Appendix A, Table A1). The study demonstrates that rises in temperature are the most noticeable in the season, the ETp values are anticipated to be high as well as increased water demand after the 2055s time period.

The highest total rainfall of 80.18mm was found by the HADCM3 GCMs of the 2090s, whereas the lowest total rainfall of 54.48mm was observed using the IPCM4 GCMs of the 2090s. During the paddy-growing season, average monthly rain-

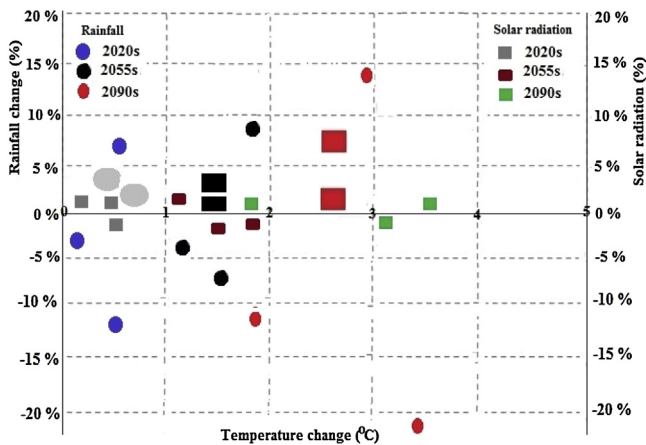


Fig. 4. The Changes in temperature vs. rainfall vs. solar radiation, for the FGOAL, HADCM3 and IPCM4 GCMs model run on SRES A1 B scenario. The three larger grey, black and red symbols show the means for the periods of 2020 s, 2055 s and 2090s. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

fall changed by -2.67 to 7.17 mm, -5.26 to 10.03 mm, and -4.93 to 15.68 mm respectively for the three GCMs (Table A1, Appendix A). The HADCM3 GCMs indicates the largest variation in rainfall change. In particular, winter crop-growing seasons, the amounts of mean solar radiation changed slightly by 0.07 – 0.16 MJ/m², -0.08 to 0.05 MJ/m², -0.10 to 0.06 MJ/m² respectively for three GCMs (Table A1, Appendix A). It indicates that the increasing rate of solar radiation is relatively lower than the increasing rate of temperature in the study sites.

Fig. 4 displays the projected changes in temperature vs rainfall vs solar radiation for the period of 2020s, 2055s and 2090s based on the SRES A1B from the outputs of the FGOAL, HADCM3 and IPCM4 GCMs. The effect of global climate change is clear, indicating itself in an average increase in temperature of 0.48 °C for 2020s, 1.54 °C for 2055s and 2.77 °C for 2090s respectively in the study site of Bangladesh. In addition, higher evapotranspiration (ET_0) demand is to be expected in this point. The solar radiation change (%) has shown in the plot with predicted the radiation change of 0.3% for 2020s, 0.07% for 2055s and 0.04% for 2090s correspondingly. Regarding rainfall change (%), it is well displayed in the plot, with projected mean shows a 3.13% decrease in rainfall for 2020s, a 1.09% decrease for 2055s and a 6.08% decrease in rainfall for 2090s. Besides, Bangladesh is predicted to increase in mean temperature overall by 1.1 °C by 2030 and by 1.6 °C by 2050, and by 2.7 °C by 2070 (IPCC 2007), while rainfall is projected to decrease by 1.2 , 1.7 , and 3.0% respectively for the same years. This conclusion is consistent with the results of IPCC (2007) and Acharjee et al. (2017) but difference with an earlier climate change studies in Bangladesh (Shahid, 2010) and also most likely due to the differences in data period and methodology.

3.2. Spatial and temporal variations under climate change

3.2.1. Changes in the crop evapotranspiration

Table 5 displays the computed crop evapotranspiration (ET_p) in the winter rice producing seasons for major climatic zones in the baseline period and three GCMs under A1B scenario. Average ET_p of four zones for the baseline in the winter rice fields were 454.29 mm. For winter rice-growing season, the highest ET_p was found in Zone-G (491.29 mm), while the lowest ET_p was observed in the zone-C (415.60 mm). Average ET_p were 459.11 mm (2020s), 474.98 mm (2055s) and 487.43 mm (2090s) in the three periods for the FGOAL GCMs with increases by 7.29% in the 2090s in comparison to the baseline. Average ET_p of the four zones were 456.11 mm (2020s),

Table 5
Projected change rates (%) in the crop evapotranspiration (ET_p) (mm) during growing season of winter paddy rice in the three GCMs compared to baseline by major climatic zones.

Variable	Zone	Baseline	FGOAL GCMs			HADCM3 GCMs			IPCM4 GCMs		
			2020s	2055s	2090s	2020s	2055s	2090s	2020s	2055s	2090s
ET_p (mm)/change rate (%)	C	415.60 (–)	420.13 (1.09)	433.97 (4.42)	451.01 (8.52)	414.86 (3.4)	447.14 (7.59)	466.95 (12.35)	420.46 (1.17)	447.87 (7.76)	478.36 (15.10)
	D	463.23 (–)	473.12 (2.13)	488.71 (5.49)	501.61 (8.49)	468.56 (1.15)	507.52 (9.56)	531.67 (14.77)	534.0 (15.2)	504.45 (8.89)	534.06 (15.28)
	F	447.03 (–)	449.37 (0.52)	466.19 (4.28)	477.61 (6.84)	446.81 (–0.05)	492.51 (10.17)	521.14 (16.57)	454.80 (1.73)	482.65 (7.96)	509.57 (13.98)
	G	491.29 (–)	493.82 (0.51)	511.04 (4.01)	518.51 (5.53)	496.21 (0.58)	529.20 (7.71)	552.53 (12.46)	500.32 (1.83)	526.22 (7.11)	549.39 (11.82)
	Average	454.29 (–)	459.11 (1.06)	474.98 (4.55)	487.43 (7.29)	456.11 (0.39)	494.09 (8.76)	518.07 (14.03)	477.41 (5.08)	490.30 (7.92)	517.84 (13.98)

494.09 mm (2055s) and 518.07 mm (2090s) in the three periods for the HADCM3 GCMs with increases by 0.39%, 8.76% and 14.03% in the 2020s, 2055s and 2090s respectively. The average change rates for the ETp were 5.08% (2020s), 7.92% (2055s), and 13.98% (2090s) in the corresponding periods for the IPCM3 GCMs. The change rate of ETp increased in four zones in the 2020s–2090s with zone-D (15.28%) resulting the highest increase in ETp in the 2090s period (Table 5).

Four climatic zones exhibit an increasing tendency of the ETp values within paddy rice-growing season in all time periods and three GCMs. This is strongly confirmed by the increasing projected temperature change rates from 0.24 °C to 0.62 °C for four zones in the 2020s, which was discussed in the previous section of the paper. In addition, the ETp displayed an increasing tendency in all zones in the 2090s. This suggests that the increased in ETp during the corresponding periods due to the increased rate of temperature is more dominant than that of solar radiation increase rate in all zones. Shahid (2011) predicted an increase of ETp by 5.8% (2050s) and 8% (2075s) during winter Boro rice in northwestern Bangladesh using the B2 scenario. This study has found to be 9.56% (2055s) and 14.77% (2085s) using HADCM3 GCMs for the same area (Zone-D) during winter rice season under A1B scenario. Mainuddin et al. (2015) also projected an increase of ETp by 4% (2030s) and 6.8% (2050s) under A1B scenario for the FGOALGCMs for Boro rice in northern Bangladesh, but this study estimated an increase of ETp by 1.09% (2020s) and 4.42% (2055s) using FGOAL GCMs under similar A1B scenario in the same area (Zone-C). This is consistent with the findings of Kirby et al. (2016), where they show that potential evapotranspiration is projected to increase similarly by the 2050 for Bangladesh. A study by Acharjee et al. (2017) predicted a decline of ETp by 6.5% and 10.9% for RCP 4.5 and 8.5, respectively for the 2050s; and by 8.3% and 17.6% for RCP 4.5 and 8.5, respectively for the 2080s using five climate models in north-west region of Bangladesh. The findings differ from the results of our study. The longer duration of growing period of paddy rice may be caused for increasing the crop evapotranspiration in future. Similarly, Islam et al. (2017) showed that an increased potential evapotranspiration will exceed the rainfall loss and lead to increase water demand in future decades.

3.2.2. Changes in the effective rainfall

Table 6 presents the projected effective rainfall (ERF) values during rice-growing season for the baseline period and three GCMs in the four climatic zones in Bangladesh. The average ERFs of winter rice fields for the baseline period were 152.95 mm. The highest ERF in the winter rice fields calculated for the zone-F was 191.14 mm, whereas the lowest ERF computed for the zone-D was 119.26 mm. The average ERFs were 151.01 mm (2020s), 152.41 (2055s) and 147.58 mm (2090s) based on FGOAL GCMs and these average were lower than that of the baseline for all period except for the 2020s. The ERF increased in four zones in the 2020s except for the zone-D. The average ERFs of four zones were 177.27 mm (2020s), 168.99 mm (2055s) and 185.34 mm (2090s) based on HADCM3 and these were 10.48% to 21.17% higher than that of the baseline period. The ERF increased in all zones of winter rice field based on the HADCM3 GCMs except zone-C where average change rates of ERF decreased by 2.89% (HADCM3, 2055s). The average rates of ERFs were –7.06% (2020s), –7.54% (2055s) and –21.61% (2090s) for the IPCM4 GCMs during all periods. In case of IPCM3 GCMs, the ERF decreased in four zones except for the zone-C in the 2020s (Table 6).

The ERF of all zones showed a decreasing trend during most of the period for the IPCM4 GCMs. On the contrary, The ERF of four zones exhibited an increasing tendency except in the 2055s for the HADCM3 GCMs, although there were some differences between the GCMs used. On other words, the northwestern region of Bangladesh includes zone-D manifested a decreasing ERF and

Table 6
Projected change rates (%) in the effective rainfall (ERF) (mm) during growing season of winter paddy rice in the three GCMs compared to baseline by major climatic zones.

Variable	Zone	Baseline	FGOAL GCMs			HADCM3 GCMs			IPCM4 GCMs		
			2020s	2055s	2090s	2020s	2055s	2090s	2020s	2055s	2090s
ERF (mm)/change rate (%)	C	142.37 (–)	148.86 (4.56)	154.90 (8.80)	146.51 (2.91)	170.16 (19.52)	138.25 (–2.89)	163.58 (14.90)	143.88 (1.06)	138.41 (–2.78)	113.92 (–19.9)
	D	119.26 (–)	101.56 (–14.8)	108.27 (–9.21)	102.63 (–13.9)	120.20 (0.78)	128.53 (7.77)	132.94 (11.47)	80.86 (–32.2)	97.67 (–18.9)	80.86 (–32.2)
	F	191.14 (–)	193.16 (1.05)	194.25 (1.62)	186.92 (–2.21)	226.85 (18.68)	222.46 (16.38)	234.82 (22.85)	190.18 (–0.50)	183.21 (–4.15)	156.17 (–18.3)
	G	159.05 (–)	160.45 (0.87)	152.24 (–4.28)	154.25 (–3.02)	191.88 (20.63)	186.75 (17.40)	210.07 (32.04)	153.67 (–3.38)	146.40 (–7.95)	128.67 (–19.1)
	Average	152.95 (–)	151.01 (–1.27)	152.41 (–0.35)	147.58 (–3.52)	177.27 (15.89)	168.99 (10.48)	185.34 (21.17)	142.14 (–7.06)	141.42 (–7.54)	119.91 (–21.6)

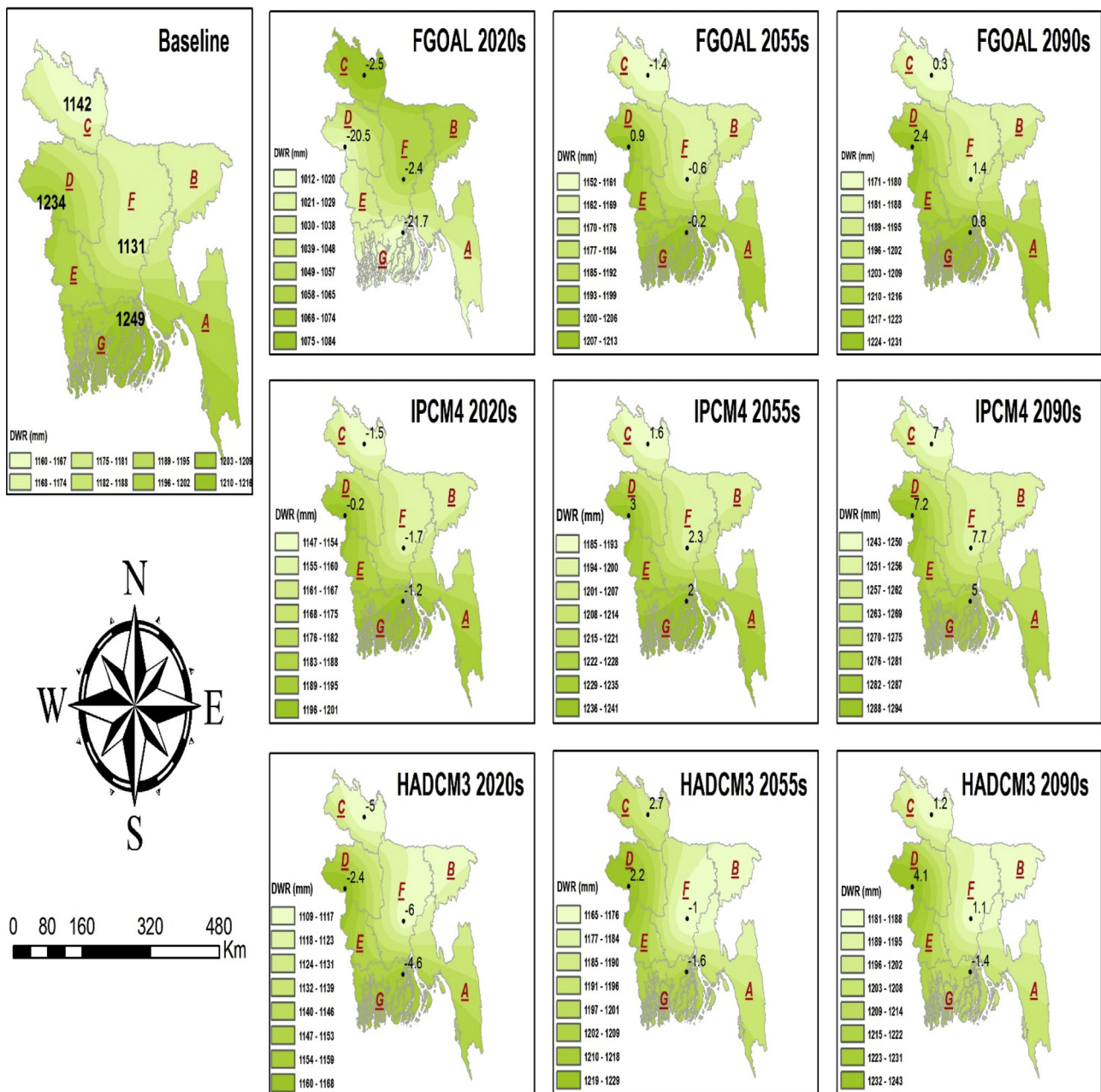


Fig. 5. The change rates of DWR for winter paddy rice in Bangladesh relative to the baseline under three GCMs for periods (bold faces indicate change rates (%) compared to baseline, underline symbols show climatic zone in the map).

central and southwestern regions including zone-F and zone-G showed the opposite trend. This study found that increased in change rates of ERF under the HADCM3 GCMs which is similar of previous study (Shahid, 2011). This finding contradicts with the earlier results of Acharjee et al. (2017), where they showed a considerable decrease of ERF in northwestern Bangladesh under RCPs 4.5 and 8.5 scenarios. The high variations of rainy days, rainfall amount and intensity in the paddy rice-growing season in Bangladesh may be caused for the higher differences in the ERF values between the three GCMs and periods. High variations (see Appendix A, Table A1) in projected rainfall amount during the winter paddy rice growing periods can be observed in three GCMs estimates. These high variations in predicted rainfall reveal a major challenge for anticipatory agricultural water management policies in Bangladesh. However, a major challenge of climate change will be to cope with the rainfall variability in future water demand. The exact quantity, by which

potential crop water requirement will change, remains uncertain due to a large variability in predicted rainfall amounts, intensities and distributions.

3.2.3. Changes in the design water requirement

The design water requirement (DWR) was derived from the GIWR model of a 5-year return period using frequency analysis. Fig. 5 shows the DWR in the baseline, and future periods (2020s, 2055s and 2090s) for the three GCMs under A1B scenario, which are used to assess the regional trends of DWRs using the ordinary kriging interpolation technique. The average DWRs in the four climatic zones for winter rice field were 1189 mm for the baseline period. The highest and lowest DWRs were 1248.52 mm in the zone-G and 1131.27 mm in the zone-F respectively for the baseline period regarding winter rice-growing season. The average DWRs were 1044.30 mm (2020s), 1185.54 mm (2055s) and

1203.74 mm (2090s) for the FGOAL GCMs corresponding periods, which shows that the average increased by 1.24% only in the 2090s in comparison to the baseline period. The average DWRs of four zones were 1136.12 mm (2020s), 1195.74 mm (2055s) and 1203.76 mm (2090s) for the HADCM3 GCMs, indicating that the average decreased by 4.44% only in the 2020s and increased by 0.57% and 1.25% in the 2055s and 2090s respectively. The average DWRs were 1175.55 mm (2020s), 1215.37 mm (2055s) and 1268.55 mm (2090s) for the IPCM4 GCMs, exhibiting that the average increased by 0.22% and 6.69% in the 2055s and 2090s respectively in comparison to baseline. The zones with the most significantly increased DWRs were zone-C, zone-D and zone-F with 1.62%, 7.03%, 2.97%, 7.23%, 2.27% and 7.67% in the 2055s and 2090s, respectively.

The regional trends of the DWR are illustrated in Fig. 5. A general decreasing trend was observed in the 2020s in all zones for three GCMs. The gentle increasing trend in northern, northwestern regions of Bangladesh around zone-C, and D in the 2055s, however zone-F and G indicated a little decrease compare to the baseline. The DWR in the 2090s demonstrated a similar to the trend of the 2055s under the FGOAL GCMs. Although, there was an increase trend of the DWR in the 2055s for the zone-C and zone-D for the HADCM3 GCMs and the DWR showed a significant decreasing trend in the central and southern region including zone-F and G in the same period. In the 2090s, the DWR illustrated a sharp increased trend in all regions of Bangladesh under HADCM3 GCMs except zone-G in comparison to baseline. In case of IPCM4 GCMs, the DWR trend was a gentle increase for northern and western part of Bangladesh in zone-C, D, F and G, in the 2055s and 2090s respectively, while marginal decreased trend was observed in all zones in the 2020s. However, there are significant differences between the GCMs; the DWR demonstrated a sharp increase tendency in northern and northwestern regions for the three GCMs in the 2055s and 2090s, while a marginal decreased trend was detected in all regions of Bangladesh for the GCMs in the 2020s period. Warmer temperature associated with increased solar radiation leads to high ET_p which might be the major reason for increasing trend of DWR in the upcoming periods. This study suggests that spatial variation of the DWR should be considered in the future planning and management of agricultural water resource in Bangladesh. This study also reveals a large impact (an increase of 4.31% for FGOALS, 3.53% for HADCM3 and 11.16% for IPCM4 by 2090s based on SRES A1B scenario) on the DWR as well as changes on individual components including ET_o, ET_p and ERF. However, those higher individual components impact cannot offset for each other and the overall combined impact is a relatively higher change in the DWR. Climate change will increase the future water requirements of winter rice, and it might be negatively affected rice yields. A study carried out by Karim et al. (2012) in Bangladesh showed that the yield of winter rice cultivar under climate change will be reduced by 33% in the end of the century. Development of a new rice variety may be useful in this case. If farmers recognize and use any late transplanting winter rice cultivars that guarantee higher yield in the climate change scenarios, the DWR can increase as well as the duration of growth period will increase. It is anticipated that this finding sends a warming signal to the future winter paddy water management in Bangladesh.

Although the shorter duration of growing stage of crops will provide some advantage to increase the cropping intensity by growing multiple crops on a land per year. As the DWR will increase in the future period as projected from our study, the agricultural water demand during the dry winter season may also increase due to the shorter Boro season to cultivate a multiple crops. This can cause an increase in future water demand each year for crop agriculture. Such an increase in future water requirement is mainly reasoned by crop phenological responses under climate change and related agricultural practice changes in the agro-ecosystems. Therefore, the

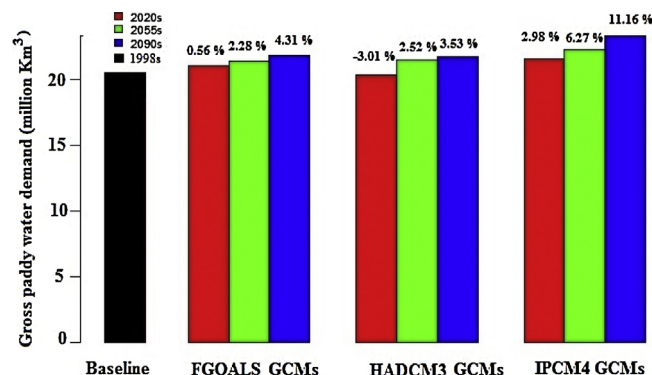


Fig. 6. Projected gross paddy water demand (GPWD) of winter paddy rice in Bangladesh for the three GCMs with future periods based on A1B scenario relative to baseline.

future agricultural practice decisions regarding the number of crops such as the cropping intensity, and the duration of growing periods are vital for the water resources management of these regions.

4. Changes in the gross paddy water demand

Gross paddy water demand (GPWD) is to be assumed that there will be no change in the paddy areas in Bangladesh for four climatic zones for the future periods. Total GPWDs for winter rice fields for each climatic zone were estimated to be 20.96 million km³ for the baseline period (Fig. 6). Gross water demand of winter paddy rice was projected to be increased the rates of change in the three GCMs under A1B scenario, by 11.16% (IPCM4 GCMs, 2090s), 6.27% (IPCM4 GCMs, 2055s), 4.31% (FGOAL GCMs, 2090s) and 3.53% (HADCM3 GCMs, 2090s) except decreased by 3.01% (HADCM3 GCMs, 2020s) from the baseline. From the results, it is clear that the highest increasing change rate of the GPWD will occur in the 2090s, especially under IPCM4 GCMs from the baseline for winter paddy rice in Bangladesh. These increasing change rates of gross paddy water demand should be taken into consideration in the planning and management of future irrigation water resource. The rates of change for both the GPWD and DWR were significant with values above 3% due to less compensating effects between the evapotranspiration and effective rainfall. This finding is in disagreement with the recent study conducted in South Korea where the average change rates of the PWD and DWR were not significant (Yoo et al., 2012).

5. Conclusions

Our results showed that the ET_p increased from the baseline in most of the period due to temperature rises in all GCMs and periods. This is because the increasing rate of temperature is relatively higher than the increasing rate of solar radiation. The ERF values increasing/decreasing rates are lesser than that of rainfall during the winter rice-growing season. Except for the FGOAL (2020s and 2055s) and HADCM3 (2020s) GCMs, the DWRs revealed an increase in most of the GCMs and periods. The change rates of the GPWD for the three GCMs ranged between 0.56% and 4.31% (FGOAL), -3.01% and 3.53% (HADCM3), and 2.98% and 11.16% (IPCM4). The average change rates of the DWR of winter rice for four climatic zones were up to 6% compared to the baseline. Prediction revealed a significant decline in future winter rainfall with enhanced higher temperature might lead to high change rates of the DWR for winter rice. It is assumed that climate change impacts on the DWR and GPWD will affect significantly in winter rice-growing season at regional scale in Bangladesh. However, the results demonstrated that south-western region exhibited a decrease in DWR, while it increased in

northern and northwestern regions in Bangladesh. For future water management of these regions, particularly to conserve groundwater resources as an alternative option, only paddy water demand management will not be a better option. So, an integrated policy takes into consideration the DWR management, the cropping patterns and conservation of recharge potential areas will be a good solution.

Some future agricultural practices, e.g. the preparation of a good crop calendar, development of new rice varieties, identification of optimal transplanting date can be implemented based on the outcomes of design water requirement and gross paddy water demand. Anticipatory water management planning at regional and national level, coping with future climate change should include suitable measures related to future irrigation demand to deal with climatic uncertainties. Thus, for future agricultural water management planning, development of flexible adaptation strategies or pathways in relation to changes in DWR may be effective to adapt to future climate change condition. In particular the spatial and temporal variations in the DWR of winter paddy rice for the upcoming periods should be taken into account in agricultural water resources management.

Although, this study has focused only on the dry season winter paddy rice; it has some limitation, for instance, cropping practices such as transplanting date, shorter or longer growing period, and crop varieties may be affected by temperature and rainfall variations and hence, affect the DWRs. The three GCMs outputs including climate data and uncertainty of downscaled LARS-WG model may have caused some setback in precision of our results. In addition, the gross irrigation water requirement (GIWR) model used vari-

ous assumptions, such as land preparation water depth, standing water level, percolation and seepage, and water loss ratio, due to limited access to Bangladesh's soil data and water management practices. Future studies concentrating on the following will be necessary: comparing with multi-GCMs ensemble models with various scenarios, improving the downscaling method, changing the rates of water requirements at the local level, and considering different cropping patterns. Though the applicability of this finding is limited, this can be used as basic tools in the development of water resources management, in terms of capacity and capability. Besides, it is expected that the outcomes of this study will be applied in minimizing the drought-risk countermeasure and implementing agriculture water resource policies in future.

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Appendix A.

Table A1

Projected monthly weather variations in four climatic zones of Bangladesh during winter paddy rice-growing season for the baseline and three GCMs based on A1B scenario.

Variables	Month	Baseline	FGOAL GCMs			HADCM3 GCMs			IPCM4 GCMs		
			2020s	2055s	2090s	2020s	2055s	2090s	2020s	2055s	2090s
Temperature (°C)	Mean	23.78	24.02	24.91	25.66	24.40	25.69	26.82	24.37	25.36	27.19
	Dec	19.30	19.76	20.82	21.65	20.21	21.43	22.72	20.11	21.18	22.95
	Jan	18.11	18.08	19.08	19.97	18.56	19.77	21.05	18.55	19.51	21.41
	Feb	21.71	21.65	22.56	23.37	21.96	23.38	24.52	22.11	23.01	24.91
	Mar	26.11	26.37	27.21	27.83	26.54	28.18	29.32	26.73	27.69	29.68
	Apl	28.46	28.87	29.62	30.27	28.85	30.63	31.56	29.09	30.08	31.88
Rainfall (mm)	May	29.02	29.38	30.18	30.87	29.32	30.73	31.75	29.62	30.68	32.31
	Total	70.15	67.48	66.94	62.98	75.41	75.99	80.18	61	65.22	54.48
	Dec	6.97	8.43	7.50	6.63	10.87	9.78	13.46	6.25	6.73	4.83
	Jan	8.67	10.48	9.05	8.57	13.02	16.09	17.48	8.41	8.39	5.59
	Feb	18.11	18.52	18.25	16.45	23.51	30.75	39.74	16.34	16.18	12.03
	Mar	41.22	32.56	34.54	33.12	33.45	31.92	34.42	31.79	32.44	22.89
Radiation (MJ/m ²)	Apl	103.17	105.78	108.26	103.58	127.61	111.38	114.4	97.29	104.98	82.67
	May	242.65	221.26	224.05	209.52	264.47	256.01	261.60	205.91	222.60	198.89
	Mean	17.55	17.71	17.62	17.55	17.50	17.54	17.47	17.60	17.45	17.61
	Dec	13.20	14.47	13.53	13.32	13.16	13.23	13.06	13.39	13.25	13.45
	Jan	14.01	13.83	13.98	13.89	13.75	13.70	13.57	13.92	13.85	13.94
	Feb	17.34	17.06	17.11	17.05	16.96	16.92	16.82	17.10	17.01	17.04
	Mar	19.78	19.83	19.84	19.73	19.66	20.07	20.04	19.84	19.71	19.82
	Apl	20.99	21.07	21.07	21.08	20.60	21.35	21.29	21.06	20.91	21.05
	May	19.98	19.97	20.17	20.23	19.49	19.97	20.05	20.27	19.98	20.31

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